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# BIOPHYSICAL EVALUATION OF INDIVIDUAL COMPONENT LEVELS AND SELECTED CONFIGURATIONS OF THE UNITED STATES MARINE CORPS COLD-WEATHER CLOTHING ENSEMBLE



United States Army
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**USARIEM TECHNICAL REPORT T18-01**

# BIOPHYSICAL EVALUATION OF INDIVIDUAL COMPONENT LEVELS AND SELECTED CONFIGURATIONS OF THE UNITED STATES MARINE CORPS COLD-WEATHER CLOTHING ENSEMBLE


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The Biophysics and Biomedical Modeling Division (BBMD) is examining a new thermal manikin testing paradigm where the measured thermal properties of individual layers of a multi-layer clothing system are used as inputs to a model that predicts the thermal characteristics of various multi-layer ensembles. Thermal and evaporative resistance measurements were completed on individual layers as well as for selected multi-layer ensembles. The measurements were performed on four different types of thermal manikins: whole-body, hand, foot, and head manikins. The measured results of the selected ensembles were compared to existing empirical equations that predict composite insulation from the clothing data for individual layers.

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## TABLE OF CONTENTS

## LIST OF FIGURES



## LIST OF TABLES

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# EXECUTIVE SUMMARY

The Biophysics and Biomedical Modeling Division (BBMD) is examining a new thermal manikin testing paradigm where the measured thermal properties of individual layers of a multi-layer clothing system are used as inputs to a model that predicts the thermal characteristics of various multi-layer ensembles. Cold-weather clothing systems are an ideal category of clothing to assess this new analytical approach due to the number of possible layering combinations. The United States Marine Corps Mountain/Cold-Weather Clothing System (MCWCS) is the first clothing system evaluated using this new method and is the focus of this technical report. Thermal manikin measurements, i.e., thermal and evaporative resistance ($R_t$ and $R_{et}$), were completed on individual layers as well as for selected multi-layer ensembles. The measurements were performed on four different types of thermal manikins: whole-body, hand, foot, and head manikins. The measured results of the selected ensembles were compared to existing empirical equations that predict composite insulation from the clothing data for individual layers.

## INTRODUCTION

During cold-weather military operations, the environment can impair Marine performance and increase the risk of cold injuries such as frostbite and hypothermia. A Marine's ability to meet operational requirements and to avoid cold injury is critical to the success of the mission. Cold-weather ensembles offer protection against cold injury, but as the level of ensemble protection increases, the bulk and weight carried also increase. Reduced mobility, flexibility, and dexterity may hinder the ability to successfully accomplish a mission. Thermal protection is an important characteristics of cold-weather ensembles that must be balanced with other clothing characteristics to meet mission requirements.

Thermal manikins, first developed by the U.S. Army in the 1940s, have been widely used to evaluate thermal performance of clothing and individual equipment (CIE) (7, 10), including cold-weather ensembles (3, 5). Typically, measurements of thermal and evaporative resistance ($R_t$ and $R_{et}$) are made on a thermal manikin for a specific configuration of CIE. These measurements are then used as input parameters for physiological models which predict health state and performance (e.g., thermal status, maximum work duration time). The predictions are specific to the exact clothing configuration measured on a thermal manikin. When the CIE is worn in the field, changes in intended configurations are likely to occur, driven by varying environmental conditions, activity levels, and personal preferences, causing model predictions to become less precise.

As an alternative to performing thermal manikin testing for all possible CIE configurations, the Biophysics and Biomedical Modeling Division (BBMD) is developing a new paradigm of testing all individual layers of a multi-layer clothing system. The goals of the new method are to (1) reduce the amount of thermal manikin work through the use of existing equations or the development of new equations that predict $R_t$ and $R_{et}$ for multi-layer configurations based on $R_t$ and $R_{et}$ measurements of individual layers; (2) investigate improvements to multi-layer clothing systems by identifying individual layers with ideal $R_t$ and $R_{et}$ properties through testing of various cold-weather clothing systems; and (3) provide a database of clothing properties for the development of a software application that will operate one of BBMD's physiological models and allow users to select different layering combinations of clothing. Measuring and documenting resistance values of individual clothing levels as well as select multi-layer configurations for the United States Marine Corps Mountain/Cold-Weather Clothing System (MCWCS) is the first milestone of this alternative testing method and will be the main focus of this technical report.

## METHODS

### MATERIALS

The MCWCS is a multi-layer system which allows Marines to select various combinations of different layers according to mission requirements and environmental conditions. Each layer plays a distinct role in providing protection from cold weather,

such as increasing insulation, wicking moisture away, and preventing air penetration. The MCWCS includes six levels of clothing plus an accessory level for camouflage (snow overwhites). Testing each of the six individual levels included three separate tests: (1) top component, (2) bottom component, and (3) top and bottom components. Level 3 was the exception because it consisted of only a top component (jacket). Descriptions of the levels along with additional accessory components for the head, hand, and foot are shown in Table 1. In addition to the individual level testing, six typical configurations composed of different combinations of the individual levels were selected for thermal manikin testing: Levels 1 and 5 (LVL 15), Levels 1, 4, and 5 (LVL 145), Levels 1, 2, and 5 (LVL 125), Levels 1, 2, 5, and 6 (LVL 1256), Levels 2, 3, and 6 (LVL 236), and Levels 1, 3, 4, and 5 (LVL 1345). For this report, the Flame Resistant Combat Ensemble was included in all ensemble configurations that include Level 4. However, the Marine Corps Combat Utility Uniform (MCCUU) is the typical battle uniform for Marines in combat. Therefore, the thermal manikin data for the MCCUU is included in Table 3 and Table 4 for comparison as an alternate Level 4 garment.

Table 1. Clothing and individual equipment descriptions

| Description | Size | NSN: 8415-01- |
|---|---|---|
| **Whole-body** | | |
| Level 1 - FR Silk-weight Undershirt and Drawers | Medium | 567-4423; 567-4033 |
| Level 2 - FR Mid-weight Grid Fleece Undershirt and Drawers | Medium | 555-3877; 555-3809 |
| Level 3 - Wind Pro Fleece Jacket | Medium Regular | 555-7571 |
| Level 4 - FR Combat Ensemble | Medium Regular | 547-1743; 547-0006 |
| Level 4a – Marine Corps Combat Utility Uniform (MCCUU) | Medium Regular | 527-1452; 527-1848 |
| Level 5 - Lightweight Exposure Suit | Medium Regular | 555-1434; 555-3019 |
| Level 6 - Extreme Cold Weather Suit | Medium Regular | 555-1279; 555-1329 |
| Snow Overwhites | Medium Regular | 555-0395; 555-0450 |
| **Head** | | |
| Hardface Microfleece Cold Weather Cap | Small/Medium | 554-9623 |
| Lightweight Balaclava | Medium/Large | 546-2742 |
| **Hand** | | |
| Light Duty FR Glove Insert | Small/Medium | 555-4406 |
| Extreme Cold Weather Mitten Liner | Medium | 555-4016 |
| Extreme Cold Weather Mitten Shell | Medium | 555-4174 |
| **Foot** | | |
| Extreme Cold Weather Suit Booties | Medium | 555-3081 |
| Darn Tough Extreme Cold Weather Mid-Calf Boot Sock | Small | N/A |

FR = Flame Resistant, NSN = National Stock Number. The first NSN listed is for the top of the level and the second is for the bottom i.e. top;bottom.

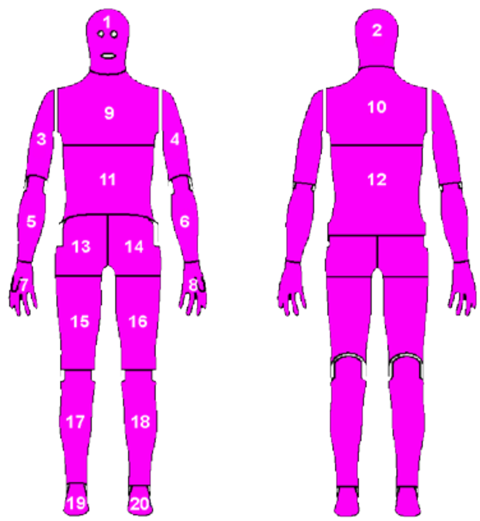
## THERMAL MANIKIN TESTING

### Whole-body Manikin

A Newton model sweating thermal manikin (Thermetrics, Seattle, WA; www.Thermetrics.com) used for testing consisted of 20 independently heated and controlled zones. At USARIEM, thermal manikin data is commonly binned into six sections corresponding to the anatomical regions used by the Six Cylinder Thermoregulatory Model (SCTM) (11, 12). Specifically, the SCTM requires clothing data for the head, torso, arm, hand, leg, and foot sections of the body. The data

collected on the head, hand, and foot manikins was used for their respective SCTM sections, while the data collected on the whole-body thermal manikin was used for the torso (manikin zones 9-14), arm (manikin zones 3-6), and leg (manikin zones 15-18) sections. See Figure 1 for location of zones.

Figure 1. Zone diagram from ThermDAC software of the whole-body thermal manikin




**Hand Manikin**

The thermal hand manikin has eight zones for measurements with an additional guard zone (zone 9) beginning around the middle of the forearm. In addition to the entire measurement area (zones 1-8) three sections of the hand manikin are of interest for the SCTM: the fingers and thumb (zones 1-5), the hand (zones 1-7), and the wrist (zone 8), see Figure 2 for zone locations. The Insert (I), Liner (L), and Shell (S) components of the mitten system listed in the Hand section of Table 1 were all tested on the hand manikin as individual components. Four composites of those individual items were also tested: Insert and Liner (IL); Insert, Liner, and Shell (ILS); Insert and Shell (IS); and Liner and Shell (LS) to determine if a clear relationship exists between the measured insulation of composite systems and the summation of individual component measurements. However, there were only four data points with the linear regression producing an $R^2$ value of 0.86. Therefore, testing of additional handwear systems is required to fully examine this relationship.

Table 2 was created to provide a comparison of the measurement areas between the whole-body thermal manikin and the other body-part manikins. The hand manikin is only a single right hand. Therefore, the surface area values are multiplied by two for comparison with similar sections of the whole-body manikin. The wrist section of the hand manikin only partially matches the forearm section of the whole-body manikin, while both the hand zones of the whole body manikin and zones 1-7 of the hand manikin (x2) have the same surface area. It is worth noting that the OR Mitten Shell extended well beyond the wrist measurement area on the hand manikin and covered the entire guard zone. Since the guard zone is not included in any calculation for $R_t$ and

$R_{et}$, the resistance of this part of the mitten is currently not accounted for and may require whole-body manikin testing for completeness.

Figure 2. Zone diagram from ThermDAC software of the thermal hand manikin


Table 2. Surface area of thermal manikins

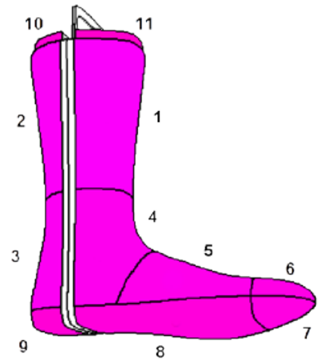
| Surface Area ($m^2$) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Manikin** | **All Zones** | **Head** | **Torso** | **Arm** | **Hand** | **Fingers** | **Leg** | **Foot** | **Toe** |
| **Whole-body Thermal Maniki** | 1.814 | 0.145 | 0.587 | 0.297 | 0.092 | - | 0.574 | 0.119 | - |
| **Head Manikin** | 0.134 | 0.134 | - | - | - | - | - | - | - |
| **Hand Manikin*** | 0.126 | - | - | 0.033 | 0.092 | 0.047 | - | - | - |
| **Foot Manikin*** | 0.202 | - | - | - | - | - | 0.075 | 0.127 | 0.014 |

*The surface areas of the hand and foot manikins are doubled.

## Foot Manikin

The thermal foot manikin has nine zones for measurements and two additional guard zones at the top of the foot, zones 10 and 11. Similar to the hand manikin, three sections are of interest for SCTM modeling: the toes (zones 6-7), the foot (zones 3-9), and the calf (zones 1-2). See Figure 3 for zone locations. The Extreme Cold Weather Suit Bootie and the Darn Tough™ Extreme Cold Weather Mid-calf Sock were each tested individually on the foot manikin. The foot manikin is only a single left foot. Therefore, the surface area values in Table 2 are multiplied by two for comparison with similar sections of the whole-body manikin. The surface area of the foot manikin, zones 3-9, is 0.127 $m^2$ which is 6.5% higher than the surface area of the foot on the whole-body manikin. Neither of the items measured on the foot manikin extended past the measurement area and therefore $R_t$ and $R_{et}$ of the entire footwear items were accounted for.

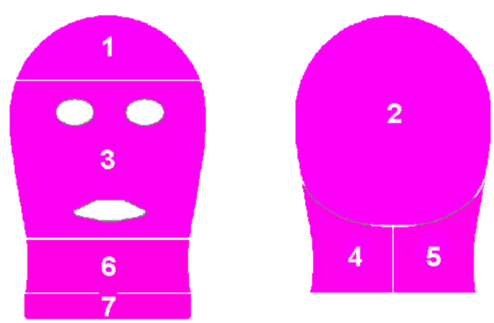
Figure 3. Zone diagram from ThermDAC software of the foot manikin




## **Head Manikin**

USARIEM's thermal head manikin is constructed differently than the other four manikins mentioned in this report, which consist of a fiberglass epoxy resin shell. The head manikin is a legacy copper thermal manikin head that was refurbished by Thermetrics. The head has six independently heated and controlled zones that make up the measurement area. There is an additional guard zone at the neck to prevent heat loss downward through the neck. See Figure 4 for zone locations. The measurement area (zones 1-6) of the head manikin has 7.3% smaller surface area than a similar section of the whole-body manikin, which consists of the face and head zones. Since the surface areas of these two sections are similar, it is not necessary to parse the head manikin data into smaller sections. The Hardface Microfleece Cold Weather Cap and Lightweight Balaclava were tested individually and together as a two-piece system on the head manikin. Similar to the handwear testing, the Balaclava extended past the measurement area to cover the guard zone, leaving a portion of the balaclava resistance unaccounted for.

Figure 4. Zone diagram from ThermDAC software of the thermal head manikin




## **Test Conditions**

All testing was conducted according to ASTM International standards F1291-16 and F2370-16 (1, 2). $R_t$ ($m^2 \cdot K \cdot W^{-1}$) was measured at an air velocity of 0.4, $m \cdot s^{-1}$ with the air temperature ($T_a$) and relative humidity ($RH$) inside the environmental chamber at

20°C and 50 %RH, respectively. $R_{et}$ (m$^2$•Pa•W$^{-1}$) was measured at an air velocity of 0.4 m•s$^{-1}$ with a $T_a$ of 35°C and an $RH$ of 40%. Three test replications were completed for each condition and each clothing configuration. Further information on the clothing parameter units and calculations can be found in Appendix B.

Testing was conducted using whole-body, hand, foot, and head sweating thermal manikins (Thermetrics, Seattle, WA). The thermal manikin systems are made up of multiple zones detailed in the previous sections; each zone is independently heated and regulated. The manikin systems are controlled, and all parameters are recorded and processed by ThermDAC software. The power to each zone was considered as the heat loss to the environment. The thermal resistance value of each region was calculated by:

$$R_t = \frac{(T_s - T_a)A}{Q} \tag{1}$$

where $T_s$ and $T_a$ are the manikin surface temperature and the ambient temperature, in Kelvin units. $A$ is the surface area of the manikin in m$^2$ and $Q$ is the power supplied to the manikin in W.

Evaporative resistance was measured in isothermal conditions $(T_s = T_a)$ and therefore calculated by:

$$R_{et} = \frac{(P_{sat} - P_a)A}{Q} \tag{2}$$

where $P_{sat}$ is the vapor pressure at the manikin surface, in Pa, with the assumption that the air is saturated with water vapor at the manikin surface. $P_a$ is the vapor pressure of the ambient environment, also in Pa. Both vapor pressure values are calculated by the Antoine equation, which is a function of temperature.

## SUM OF LAYER INSULATION

In the past forty years, a large number of regression equations have been developed to estimate $R_t$ values of multi-layer clothing ensembles based on the sum of the $R_t$ of individual clothing components (6, 8). The regression equations are typically in clo units. Therefore, for use with these equations, thermal resistance will be converted to clo units as

$$I_t = 6.45 \cdot R_t \tag{3}$$

As is customary in ASTM F1291-16, the variable will be changed from $R$ to $I$ when using clo units. Two simple equations to predict whole-body insulation values are Equation 4, which is slightly modified from the equation used in Olesen 1985, and Equation 5 (6, 8):

$$I_{cle} = \sum I_{cle,i} \tag{4}$$

$$I_{cle} = 0.838 \cdot \sum I_{cle,i} \tag{5}$$

where $I_{cle,i}$ is the effective thermal resistance of the individual clothing layers, in clo units and $I_{cle}$ is the effective thermal resistance of the composite ensemble, in clo units. Typically, intrinsic thermal resistance is calculated as

$$I_{cl} = I_t - \left(\frac{I_a}{f_{cl}}\right) \quad (6)$$

where $I_t$ is the total thermal resistance of clothing measured on the thermal manikin, $I_a$ is the thermal resistance of the boundary air layer of the nude thermal manikin, and $f_{cl}$ is the clothing area factor. The effective thermal resistance is calculated as

$$I_{cle} = I_t - I_a \quad (7)$$

The benefit of using effective instead of intrinsic resistance is that measuring or estimating $f_{cl}$ is not necessary, which can be cumbersome to calculate and inaccurate to estimate (4). Also, the summation equations using effective resistance are comparable in accuracy to prediction equations using intrinsic resistance that require $f_{cl}$.

## RESULTS

The whole-body thermal manikin testing results for the individual clothing levels are listed in Table 3 and Table 4 and for selected ensembles in Table 5 and Table 6. Testing results for the head, hand, and foot manikins are listed in Table 7, Table 8, and Table 9, respectively. Nude values for all manikins are included the top of each table for convenience of calculating intrinsic and effective resistance values. For sections consisting of more than one zone, the parallel weighted average of these zone groupings are the reported values. For the whole-body manikin testing, the head, hand, and foot sections were typically not dressed, but data are still included in the tables for reference. The leg section of the foot manikin and the wrist section of the hand manikin are partial sections and therefore the resistance values are not expected to compare well with the same sections from the whole-body manikin.

In Table 10, the prediction results from Equations 4-5 were calculated and compared to the measured thermal resistance values. The results and prediction equations are specifically for the whole-body $R_t$ values. The percent difference between the predicted and measured values is listed at the end of each section. The average percent difference was 11% for Equation 4 and 13% for Equation 5.

Table 3. Total thermal resistance for individual clothing levels

| Thermal Resistance, $R_t$ ($m^2K/W$) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | All Zones | Head | Torso | Arm | Hand | Leg | Foot |
| **Nude** | | | | | | | |
| | 0.11 | 0.12 | 0.13 | 0.11 | 0.09 | 0.10 | 0.09 |
| **LVL 1 - Silk Weight Underwear** | | | | | | | |
| **T** | 0.13 | 0.11 | 0.24 | 0.16 | 0.09 | 0.09 | 0.09 |
| **B** | 0.12 | 0.11 | 0.15 | 0.10 | 0.09 | 0.13 | 0.09 |
| **TB** | 0.15 | 0.11 | 0.25 | 0.16 | 0.09 | 0.14 | 0.09 |
| **LVL 2 - Grid Fleece** | | | | | | | |
| **T** | 0.13 | 0.11 | 0.28 | 0.20 | 0.09 | 0.09 | 0.10 |
| **B** | 0.13 | 0.11 | 0.15 | 0.10 | 0.09 | 0.17 | 0.09 |
| **TB** | 0.17 | 0.11 | 0.28 | 0.20 | 0.09 | 0.17 | 0.10 |
| **LVL 3 - Wind Pro Jacket** | | | | | | | |
| **T** | 0.14 | 0.12 | 0.31 | 0.28 | 0.09 | 0.09 | 0.08 |
| **LVL 4 - FR Combat Ensemble** | | | | | | | |
| **T** | 0.13 | 0.11 | 0.24 | 0.22 | 0.09 | 0.09 | 0.09 |
| **B** | 0.14 | 0.11 | 0.16 | 0.10 | 0.09 | 0.19 | 0.11 |
| **TB** | 0.18 | 0.11 | 0.25 | 0.22 | 0.09 | 0.20 | 0.09 |
| **LVL 4a - Marine Corps Combat Utility Uniform** | | | | | | | |
| **TB** | 0.20 | 0.12 | 0.28 | 0.24 | 0.09 | 0.22 | 0.10 |
| **LVL 5 - Lightweight Exposure Suit** | | | | | | | |
| **T** | 0.13 | 0.12 | 0.24 | 0.21 | 0.09 | 0.09 | 0.08 |
| **B** | 0.14 | 0.11 | 0.16 | 0.10 | 0.09 | 0.19 | 0.09 |
| **TB** | 0.18 | 0.12 | 0.26 | 0.21 | 0.09 | 0.19 | 0.09 |
| **LVL 6 - Extreme Cold Weather** | | | | | | | |
| **T** | 0.16 | 0.11 | 0.68 | 0.51 | 0.09 | 0.09 | 0.09 |
| **B** | 0.15 | 0.11 | 0.17 | 0.10 | 0.09 | 0.34 | 0.10 |
| **TB** | 0.28 | 0.11 | 0.68 | 0.51 | 0.09 | 0.36 | 0.10 |
| **Accesory - Snow Overwhites** | | | | | | | |
| **T** | 0.14 | 0.16 | 0.28 | 0.23 | 0.11 | 0.09 | 0.09 |
| **B** | 0.13 | 0.11 | 0.15 | 0.10 | 0.09 | 0.18 | 0.09 |
| **TB** | 0.18 | 0.15 | 0.26 | 0.21 | 0.10 | 0.18 | 0.09 |

T = top i.e., shirt, B = bottom i.e., trousers, and TB = top and bottom i.e., shirt and trousers.  LVL = level.

Table 4. Total evaporative resistance for individual clothing levels

| | Evaporative Resistance, $R_{et}$ ($m^2Pa/W$) | | | | | | |
|---|---|---|---|---|---|---|---|
| | All Zones | Head | Torso | Arm | Hand | Leg | Foot |
| **Nude** | | | | | | | |
| | 13.8 | 18.8 | 19.2 | 13.2 | 10.4 | 12.6 | 10.0 |
| **LVL 1 -Silk Weight Underwear** | | | | | | | |
| **T** | 16.3 | 17.0 | 34.4 | 20.1 | 12.5 | 10.8 | 11.2 |
| **B** | 15.5 | 17.7 | 19.9 | 12.8 | 11.9 | 15.5 | 10.5 |
| **TB** | 18.8 | 16.9 | 33.6 | 19.5 | 11.2 | 15.9 | 10.7 |
| **LVL 2 - Grid Fleece** | | | | | | | |
| **T** | 17.0 | 18.5 | 35.0 | 27.6 | 15.2 | 10.7 | 10.3 |
| **B** | 17.2 | 17.0 | 20.8 | 12.8 | 11.8 | 21.8 | 10.3 |
| **TB** | 22.7 | 16.7 | 36.8 | 28.2 | 14.8 | 21.2 | 10.4 |
| **LVL 3 - Wind Pro Jacket** | | | | | | | |
| **T** | 17.2 | 17.3 | 42.2 | 36.5 | 11.0 | 10.7 | 9.2 |
| **LVL 4 - FR Combat Ensemble** | | | | | | | |
| **T** | 17.6 | 18.1 | 37.3 | 38.9 | 11.7 | 10.8 | 11.5 |
| **B** | 19.5 | 16.3 | 20.2 | 12.4 | 14.7 | 36.9 | 13.1 |
| **TB** | 27.4 | 16.3 | 34.2 | 34.7 | 11.2 | 37.9 | 14.5 |
| **LVL 4a - Marine Corps Combat Utility Uniform** | | | | | | | |
| **TB** | 26.3 | 15.0 | 32.9 | 32.3 | 11.1 | 44.4 | 10.8 |
| **LVL 5 - Lightweight Exposure Suit** | | | | | | | |
| **T** | 17.9 | 18.5 | 34.2 | 45.7 | 12.8 | 11.2 | 10.6 |
| **B** | 20.9 | 17.9 | 23.6 | 12.9 | 12.0 | 46.0 | 11.1 |
| **TB** | 31.9 | 17.6 | 47.0 | 47.1 | 12.7 | 47.6 | 11.3 |
| **LVL 6 - Extreme Cold Weather** | | | | | | | |
| **T** | 19.7 | 16.8 | 74.1 | 104.1 | 14.0 | 10.5 | 10.4 |
| **B** | 21.4 | 16.8 | 21.4 | 12.2 | 14.7 | 60.7 | 14.1 |
| **TB** | 42.4 | 14.9 | 127.7 | 96.8 | 12.2 | 62.4 | 13.8 |
| **Accesory - Snow Overwhites** | | | | | | | |
| **T** | 19.3 | 26.7 | 43.0 | 35.2 | 14.2 | 11.5 | 11.6 |
| **B** | 20.2 | 18.0 | 22.4 | 13.5 | 17.9 | 32.1 | 11.5 |
| **TB** | 28.3 | 25.4 | 40.9 | 32.9 | 13.2 | 33.0 | 11.3 |

T = top i.e., shirt, B = bottom i.e., trousers, and TB = top and bottom i.e., shirt and trousers. LVL = level.

Table 5. Total thermal resistance for recommended configurations

| Clothing Configuration | Thermal Resistance, $R_t$ ($m^2K/W$) | | | | | | |
|---|---|---|---|---|---|---|---|
| | All Zones | Head | Torso | Arm | Hand | Leg | Foot |
| Nude | 0.10 | 0.12 | 0.13 | 0.10 | 0.08 | 0.09 | 0.09 |
| LVL 15 | 0.23 | 0.17 | 0.34 | 0.26 | 0.09 | 0.27 | 0.14 |
| LVL 145 | 0.27 | 0.18 | 0.41 | 0.35 | 0.09 | 0.34 | 0.14 |
| LVL 125 | 0.28 | 0.18 | 0.43 | 0.34 | 0.12 | 0.32 | 0.14 |
| LVL 1256 | 0.39 | 0.17 | 0.90 | 0.64 | 0.12 | 0.54 | 0.15 |
| LVL 236 | 0.39 | 0.18 | 0.97 | 0.76 | 0.11 | 0.48 | 0.15 |
| LVL 1345 | 0.31 | 0.18 | 0.62 | 0.45 | 0.09 | 0.34 | 0.14 |

LVL 15 = Levels 1 & 5; LVL 145 = Levels 1, 4, & 5; LVL 125 = Levels 1, 2, & 5; LVL 1256 = Levels 1, 2, 5, & 6; LVL 236 = Levels 2, 3, & 6; LVL 1345 = Levels 1, 3, 4, & 5

Table 6. Total evaporative resistance for recommended configurations

| Clothing Configuration | Evaporative Resistance, $R_{et}$ ($m^2Pa/W$) | | | | | | |
|---|---|---|---|---|---|---|---|
| | All Zones | Head | Torso | Arm | Hand | Leg | Foot |
| Nude | 12.9 | 18.5 | 17.5 | 12.3 | 9.3 | 11.0 | 9.3 |
| LVL 15 | 38.6 | 25.5 | 62.2 | 52.9 | 11.3 | 60.3 | 13.8 |
| LVL 145 | 42.4 | 26.8 | 79.8 | 67.7 | 10.8 | 71.5 | 13.2 |
| LVL 125 | 43.1 | 26.3 | 76.3 | 56.8 | 14.4 | 65.0 | 14.2 |
| LVL 1256 | 56.9 | 25.8 | 198.6 | 127.3 | 14.8 | 87.9 | 14.7 |
| LVL 236 | 52.1 | 26.3 | 162.4 | 112.4 | 14.0 | 66.4 | 15.4 |
| LVL 1345 | 44.9 | 32.6 | 103.4 | 68.4 | 11.1 | 61.8 | 14.4 |

LVL 15 = Levels 1 & 5; LVL 145 = Levels 1, 4, & 5; LVL 125 = Levels 1, 2, & 5; LVL 1256 = Levels 1, 2, 5, & 6; LVL 236 = Levels 2, 3, & 6; LVL 1345 = Levels 1, 3, 4, & 5

Table 7. Total resistance values of headwear items

| Headwear Item | $R_t$ ($m^2K/W$) | $R_{et}$ ($m^2Pa/W$) |
|---|---|---|
| | Head | Head |
| Nude | 0.09 | 10.9 |
| Hard Face Microfleece Cap | 0.14 | 15.4 |
| USMC Protective Face Shield | 0.15 | 16.5 |
| Cap and Shield | 0.20 | 23.4 |

Table 8. Total resistance values of handwear items

| Handwear Items | Thermal Resistance, $R_t$ ($m^2K/W$) | | | | Evaporative Resistance, $R_{et}$ ($m^2Pa/W$) | | | |
|---|---|---|---|---|---|---|---|---|
| | All Zones | Wrist | Hand | Fingers | All Zones | Wrist | Hand | Fingers |
| Nude | 0.07 | 0.08 | 0.07 | 0.06 | 8.2 | 9.7 | 7.8 | 5.9 |
| I | 0.12 | 0.13 | 0.11 | 0.10 | 19.0 | 23.1 | 17.9 | 15.2 |
| L | 0.26 | 0.23 | 0.27 | 0.24 | 122.9 | 120.0 | 126.4 | 130.1 |
| S | 0.29 | 0.29 | 0.30 | 0.28 | 69.9 | 81.3 | 66.6 | 58.3 |
| IL | 0.26 | 0.23 | 0.27 | 0.24 | 127.6 | 187.8 | 115.1 | 112.7 |
| ILS | 0.35 | 0.40 | 0.34 | 0.31 | 174.6 | 260.7 | 157.1 | 154.5 |
| IS | 0.31 | 0.32 | 0.30 | 0.28 | 77.4 | 105.2 | 70.7 | 61.6 |
| LS | 0.36 | 0.42 | 0.34 | 0.33 | 174.0 | 240.1 | 159.6 | 154.2 |

I = insert, L = liner, and S = shell.

Table 9. Total resistance values of footwear items

| Footwear Items | Thermal Resistance, $R_t$ ($m^2K/W$) | | | | Evaporative Resistance, $R_{et}$ ($m^2Pa/W$) | | | |
|---|---|---|---|---|---|---|---|---|
| | All Zones | Leg | Foot | Toe | All Zones | Leg | Foot | Toe |
| Nude | 0.08 | 0.07 | 0.09 | 0.06 | 10.7 | 10.3 | 11.0 | 6.5 |
| ECW Bootie | 0.17 | 0.10 | 0.31 | 0.20 | 27.8 | 14.1 | 65.6 | 73.5 |
| Darn Tough Sock | 0.13 | 0.12 | 0.15 | 0.11 | 14.7 | 15.4 | 14.4 | 8.5 |

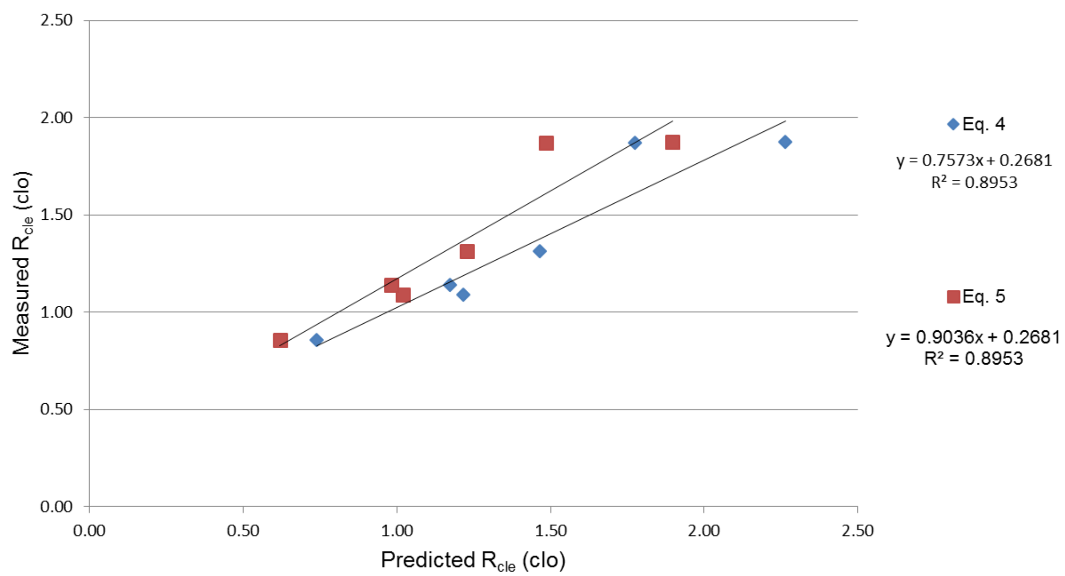
Table 10. Predicted and measured effective thermal resistance of ensembles

| **Effective Thermal Resistance, $R_{cle}$ (clo), Measured and Predicted Values** | | | | | | |
|---|---|---|---|---|---|---|
| | LVL 15 | LVL 145 | LVL 125 | LVL 1256 | LVL 236 | LVL 1345 |
| Measured | 0.86 | 1.09 | 1.14 | 1.87 | 1.87 | 1.31 |
| Eq. 4 | 0.74 | 1.21 | 1.17 | 2.26 | 1.77 | 1.46 |
| Eq. 5 | 0.62 | 1.02 | 0.98 | 1.90 | 1.49 | 1.23 |
| %Diff. (Eq. 4) | -13.8% | 11.4% | 2.8% | 20.9% | -5.2% | 11.6% |
| %Diff. (Eq.5) | -27.7% | -6.6% | -13.8% | 1.3% | -20.5% | -6.4% |

LVL 15 = Levels 1 & 5; LVL 145 = Levels 1, 4, & 5; LVL 125 = Levels 1, 2, & 5; LVL 1256 = Levels 1, 2, 5, & 6; LVL 236 = Levels 2, 3, & 6; LVL 1345 = Levels 1, 3, 4, & 5

In Figure 5, the measured values of the selected clothing ensembles were plotted against the predicted values from both Equation 4 and Equation 5. The $R^2$ value for both linear regressions is 0.8953. However, if LVL 236 is removed from the plot, the $R^2$ value becomes 0.9914. Further expansion of the cold-weather clothing database will be required to determine if LVL 236 truly is an outlier and what may be the cause.

Figure 5. Measured vs. predicted effective thermal resistance




## DISCUSSION

This study measured clothing properties of select configurations as well as for each individual layer of the MCWCS. This approach is necessary for conducting a proper assessment of cold-weather ensembles that protect Marines from cold injury, which includes life-threatening injuries such as hypothermia and hand or foot injuries such as frostbite. Hypothermia may be caused by inadequate ensemble insulation, while injuries to the extremities may be caused by inadequate insulation of gloves and

boots. Due to uneven insulation, regional heat loss and thermal sensation vary over body regions during exposure in cold environments (9). From the perspective of cold protection, both regional and whole-body values of clothing biophysical properties are critical. Thus, our new method provides more accurate information on cold protection when compared to the traditional method.

The benefit of performing testing with the head, hand, and foot manikins is to measure $R_t$ and $R_{et}$ with greater accuracy and flexibility. One major source of inaccuracy for $R_{et}$ measurements of handwear and footwear on the whole-body manikin is from water accumulating in the handwear and footwear while the manikin is “sweating”. To address this, holes are typically cut near the fingertips of the handwear or holes are drilled in the soles of footwear to allow for drainage, creating a source of error. Alternatively, the hand manikin is oriented with the fingers pointing up, so in the event that there is excess “sweat”, it will not accumulate in the glove. Excessive “sweat” dripping off the hand manikin is also not ideal. However, sweat rates are easier to control and monitor when using the hand manikin compared to the whole-body manikin. USARIEM’s foot manikin is oriented in the same manner as the whole-body manikin, with the sole having the lowest elevation. However, there will be more control of foot manikin “sweating” due to fewer zones that may be inadvertently dripping “sweat” into the footwear compared to the leg and torso zones of the whole-body manikin. The hand manikin and foot manikin test setups as just described, along with careful control of manikin sweat rates, should allow testing to proceed without altering the handwear or footwear for “sweat” drainage.

Another benefit of using multiple manikins is the flexibility provided through the existence of more zones within each body part, allowing for the selection of smaller measurement areas. For example, if the objective of particular modeling projects is to model the worst-case scenario, the $R_t$ and $R_{et}$ measurements of typically vulnerable sections such as the toes or fingertips may be selected and used as input for the hand and foot SCTM sections. Awareness of where the measurement area ends on each body part is necessary to understand if there is any portion of the CIE resistance that is unaccounted for. Potential inaccuracies could occur if comparing two CIE components, with one CIE item extending beyond the measurement area and the other item not. Proper handling of zone grouping and sweat control is necessary to improve accuracy of thermal manikin testing through use of body-part manikins.

The fact that seven of the twelve predictions in Table 10 have a percent difference of 10% to 27.7% indicates further work is required to increase the accuracy of equations that predict the sum of individual component insulation. A potential path for improvement may be to develop equations for specific body regions or to develop equations based on clothing categories, i.e., cold-weather clothing. BBMD is currently in the process of expanding our cold-weather clothing dataset, using testing methods similar to those described in this report.

## CONCLUSIONS

For convenience, complete ensembles may be tested on the whole-body thermal manikin and the results for all sections of clothing data may be entered into SCTM. However, body-part manikins may be used to complete testing simultaneously or at a later time and may provide greater accuracy and control for the head, hand, and foot sections. Data in this report was used to examine existing equations that predict the sum of thermal resistance for individual clothing ensemble components. Evaluations of additional cold-weather clothing systems will be needed to validate the prediction equations or demonstrate the need for new equations that estimate the thermal and evaporative resistance from the thermal characteristics of individual items. Measured resistance values of individual clothing levels as well as select multi-layer configurations provide scientifically-valid reference values for further development of the MCWCS.

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# APPENDIX A

## PICTURES OF MEASURED CLOTHING ITEMS

Figure 1. Level 1, Flame Resistant Silk-Weight Undershirt and Drawers

Figure 2. Level 2, Flame Resistant Mid-weight Grid Fleece Undershirt and Drawers

Figure 3. Level 3, Wind Pro® (Polartec®, Lawrence, MA) Fleece Jacket

Figure 4. Level 4, Flame Resistant Combat Ensemble

Figure 5. Level 4a, Marine Corps Combat Utility Uniform

Figure 6. Level 5, Lightweight Exposure Suit

Figure 7. Level 6, Extreme Cold Weather Suit

Figure 8. Accessory, Snow Overwhites

Figure 9. Hardface® Microfleece Cold Weather Cap (Polartec®, Lawrence, MA)


Figure 10. Lightweight Balaclava

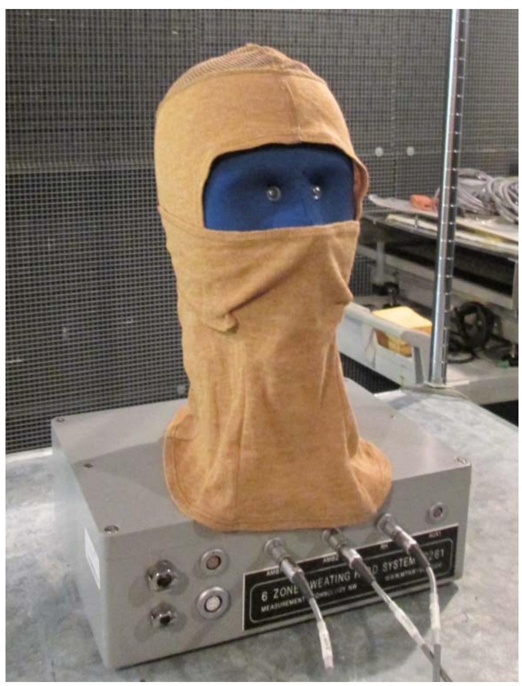

Figure 11. Light Duty Flame Resistant Glove Insert

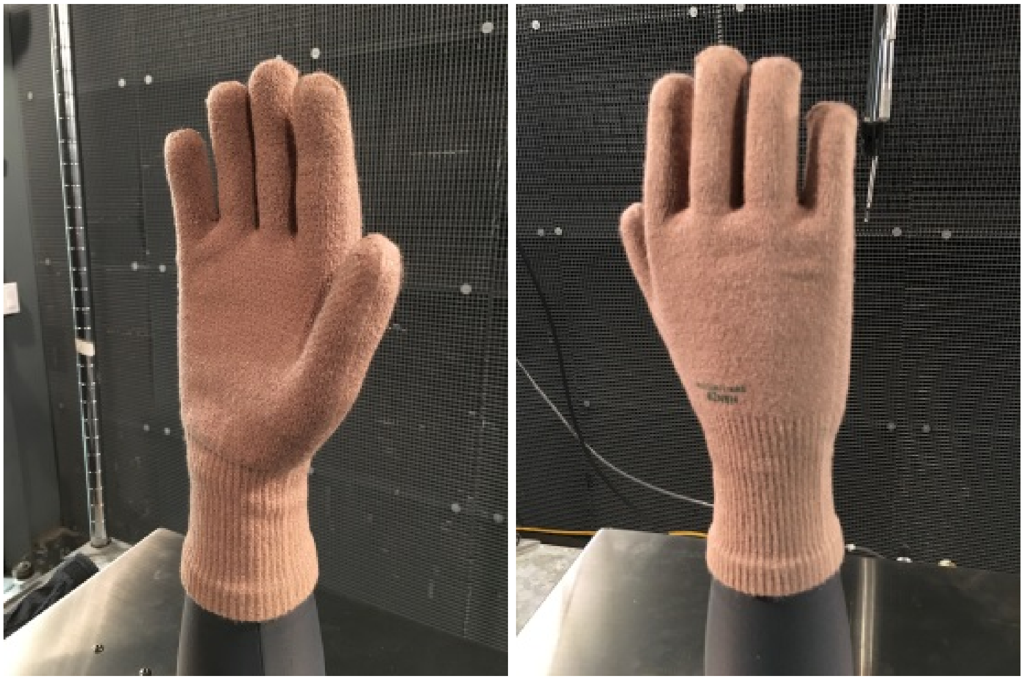

Figure 12. Extreme Cold Weather Mitten Liner

Figure 13. Extreme Cold Weather Mitten Shell

Figure 14. Extreme Cold Weather Mid-Calf Boot Sock (Darn Tough™, Northfield, VT)

Figure 15. Extreme Cold Weather Suit Booties (part of Level 6)

## APPENDIX B

## CLOTHING PARAMETER DISCUSSION

The physical measure of resistance to convection, conduction, and radiation due to clothing is defined by a general clothing property, thermal resistance ($R_t$) in K•m$^2$/W. Thermal resistance is synonymous with insulation and may be expressed in clo units, with 1 clo equal to 0.155 K•m$^2$/W. The benefit of using clo units is the point of reference to an arbitrary clothing item; a standard men's suit has the approximate insulation of 1 clo. To provide a general sense of a realistic upper limit of insulation, a heavy winter clothing ensemble may have an insulation value of approximately 4 clo.

> "The value of [1] clo was selected as roughly the insulation value of typical indoor clothing, which should keep a resting man (producing heat at the rate of 58 W/m$^2$) comfortable in an environment at 21°C, air movement 0.1 m/s." (ASTM F1291-16).

Evaporative resistance ($R_{et}$) is the measure of resistance to evaporative heat transfer due to clothing, with SI units of Pa•m$^2$/W. Typically, when clo units are used for insulation, $i_m$/clo is used instead of evaporative resistance, where $i_m$ is the permeability index developed by Woodcock (1962) and is calculated by

$$i_m = \frac{60.6515\ [\frac{\mathrm{Pa}}{\mathrm{K}}] \cdot R_t}{R_{et}}$$

> "An $i_m$ of zero indicates that the clothing system allows no evaporative heat transfer. An $i_m$ of one indicates that the clothing system achieves the theoretical maximum evaporative heat transfer allowed by its insulation." (ASTM F1868-17).

For common indoor clothing, the value of $i_m$ is approximately 0.45 and although the theoretical maximum is 1.0, $i_m$ measurements on thermal manikins at USARIEM do not typically exceed 0.60, even for nude manikin measurements.

# APPENDIX C

## ACRONYM DEFINITIONS

| | |
|---|---|
| BBMD | Biophysics and Biomedical Modeling Division |
| CIE | Clothing and Individual Equipment |
| $f_{cl}$ | Clothing area factor |
| $I_a$ | Insulation of the boundary air layer of a nude thermal manikin |
| $I_{cl}$ | Intrinsic insulation of an ensemble |
| $I_{cle}$ | Effective insulation |
| $I_{cle,l}$ | Effective insulation of a garment or layer of an ensemble |
| $I_t$ | Total insulation (clo units) |
| LVL | Level (clothing layers) |
| MCCUU | Marine Corps Combat Utility Uniform |
| MCWCS | Mountain Cold-weather Clothing System |
| $R_{et}$ | Total evaporative resistance |
| RH | Relative Humidity |
| $R_t$ | Total thermal resistance (SI Units) |
| SCTM | Six Cylinder Thermoregulatory Model |
| SI | International System of Units (Système International) |
| $T_a$ | Ambient temperature |